Modified Fuzzy PID Control for Networked Control Systems with Random Delays

Yong-can Cao and Wei-dong Zhang

***Abstract*—**To deal with random delays in Networked Control System (NCS), Modified Fuzzy PID Controller is introduced in this paper to implement real-time control adaptively. Via adjusting the control signal dynamically, the system performance is improved. In this paper, the design process and the ultimate simulation results are represented. Finally, examples and corresponding comparisons prove the significance of this method.

***Keywords*—**Fuzzy Control, Networked Control System, PID, Random Delays

I. Introduction

NOWDAYS, many industry companies have shown their great interest in Networked Control System because of their convenience in data sharing and remote manipulation [1]. Meanwhile, the IEFE has set up a new edition of IP version IPv6. This IPv6 has more flexibility and higher efficiency as well as adds new service to deal with real-time data. However, there are many problems along with NCS itself because of the uncertainties in network communication. For example, as the delays in NCS are random, the classic controllers can't be applied to NCS directly. Chan and Özgüner[2] developed a new queuing methodology for controlling an NCS on random delay networks, utilizing probabilistic information along with the number of packets in a queue to improve state prediction. As a matter of fact, this method is not a real algorithm, but a scheme to predict state variables. Göktas [3] designed a networked controller in the frequency domain using robust control theory. The delays in NCS are treated as simultaneous multiplicative perturbation. Naif B. Almutairi and Mo-Yuen Chow [4][5] proposed an intelligent controller using fuzzy logic on top of a PI gain to adaptively compensate for the IP network-induced time delay in time-delay sensitive Networked Control System applications. Partial adaptation scheme and Adaptive Full Modulation (AFM) are presented in [4] and [5] separately.

In order to deal with nonlinear in random delays effectively, a new method that applies Fuzzy Logic into PID controller is presented in this paper. In fact, the delays in NCS can be regarded as the sum of many functions with different orders. Therefore, classic PID controller is modified here to introduce high-order information, which can accurately reflect the delays. In addition, the parameters in Modified Fuzzy Controller can dynamically adapt the change of delays because of the adaptation of the Fuzzy Logic. Thus the dynamic performance of Networked Control System can be improved with this method.

This paper is organized as follows. Section 2 describes the problems in NCS. Section 3 and 4 are the results and simulations respectively. The conclusions and future work are presented in section 5.

II. Problem Formulation and Preliminaries

In this section, an example about DC motor is used in our analysis. The remote control through network consists of four parts: plant (DC motor), sensor, controller (in remote area), and actuator. As is shown in Fig.1:

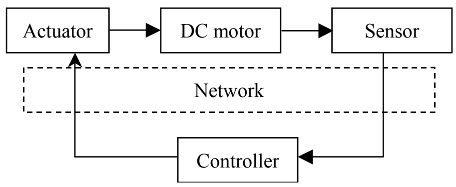

Fig. 1 A diagram for NCS

The plant DC motor can be described as state-space form. For example we can define DC motor as follows:

$$\dot{x} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} x + bu \; ; \quad (1)$$

$$y = \begin{bmatrix} c_1 & c_2 \end{bmatrix} x \quad (2)$$

Where u, x and y are control variables, state variables, and output respectively. As the signals are transmitted from sensor to controller and from controller to plant through network, the controller and plant will receive corresponding signals a short time later after they were sent out. That is:

$$u_n = u(t - \tau_{CA}) \; ; \quad (3)$$

$$y_n = y(t - \tau_{SC}) \; ; \quad (4)$$

$$\dot{x} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} x + bu(t - \tau) \quad (5)$$

Here u_n, y_n are the n_{th} control signal and output signal respectively. And τ_{CA}, τ_{SC} refer to the delay time from controller to plant and from the sensor to controller. τ_{CA} and τ_{SC} vary in the control process. Therefore, the controller needs to adapt not only the existing delays but also its inconstancy. Here, a good idea is to apply PID controller into this system. However, in order to deal with the unreliable delays effectively, the classical PID controller should be modified appropriately.

When the delays are large, the system shows a higher overshoot, longer response time; while the delays are small, the system is more stable. Obviously, the parameters of PID can be correspondingly adjusted to adapt with the change of delays. Considering the requirement, Modified PID Fuzzy Logic Control (MPFLC), then, is introduced into this field as fuzzy logic theory has shown its great benefit to deal with uncertainty in control field.

III. PROBLEM ANALYSIS

In this section, the design process will be presented. The control signal depends mainly on the error between reference and the output. For a classical PID controller, the relationship between error and control is as follows:

$$u(i) = K_p e_i + K_i \sum e_i + K_d (e_i - e_{i-1}) \qquad (6)$$

where K_p, K_i and K_d refers to proportional, integral and differential parameters. From the formula (6) we know that the error, the sum of error, and the change of error in PID determine the control. In this paper, a new method is represented to determine the control signal, that is:

$$u(i) = K_i e_i + K_p (e_i - e_{i-1}) + K_d (e_i - 2e_{i-1} + e_{i-2}) \qquad (7)$$

where $e_i - 2e_{i-1} + e_{i-2}$ is the rate of error change ($d^2 e(t)/dt^2$).

The rate of error change is also an important factor, especially in NCS with inconstant delay time. In formula (7), the integral part is omitted, compared with classical PID, the reason is that: when the error between reference and output is relatively large, the parameter K_i is small or 0 because the integration part is useless and the main task is to increase the response speed; when the error is relatively small, in classical PID controller, the fact that K_p is small and K_i is relatively large in order to eliminate the stable error can be replaced by adding the rate of error change to adjust the error change and error. When the error change is positive, the rate of error change is negative; vice versa.

In addition to this method mentioned above, the Jump System Approach [6], a kind of hybrid systems, has been proposed to deal with the random communication delays.

1. Membership functions

The membership functions for the error, the change of error

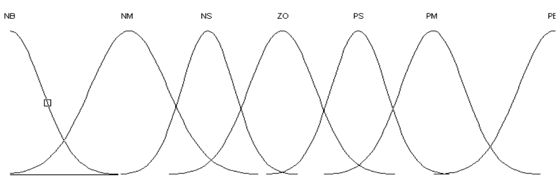

Fig. 2 Membership functions for the error

and the rate of error change can be defined over $e \in (-r, r)$. The membership functions NB (negative big), NM (negative middle), NS (negative small), ZO (zero), PS (positive small), PM (positive middle), PB (positive big) can be depicted in Fig.2 (please see [7] in detail).

2. Fuzzy Control Rules (FCR)

The Fuzzy Control Rules are given in determining the control signal according to the error, the sum of the error and the change of error. This relationship between the error signal and control signal is mainly based on the experience. For example, if both the error and the change of error are NB, the control signal should be PB in order that the systems can response quickly; while if the error is NB and the change is PB, the diversity of control signal appears in conflicting systems.

FCR describes the fuzzy relationship among the error, the change of error and the control signal, that is, through searching FCR, corresponding error information gives related control signal. The FCR can be described as follows:

$$K_p^{k+1} = K_p + \Delta K_p; \; K_i^{k+1} = K_i + \Delta K_i;$$
$$K_d^{k+1} = K_d + \Delta K_i;$$

The Fuzzy control rules can be seen in Table 1.

TABLE I (a)
FUZZY CONTROL RULES

EC \ E	NB	NM	NS
PB	ZE/PM/PS	ZE/PM/PS	NS/PB/ZE
PM	ZE/PB/NB	ZE/PS/NB	NS/PB/ZE
PS	PM/ZE/NB	PS/ZE/NB	ZE/ZE/NM
ZE	PB/NS/NS	PM/NS/NS	PS/NS/NS
NS	PB/ZE/NB	PB/ZE/NB	PM/ZE/NM
NM	PB/PB/NB	PB/PS/NB	PM/PS/NM
NB	PB/PM/PS	PB/PB/PS	PM/PB/ZE

TABLE I (b)
FUZZY CONTROL RULES

EC \ E	ZE	PS	PM	PB
PB	NM/PB/ZE	NM/PB/ZE	NM/PS/PS	NM/PS/NB
PM	NM/PS/NS	NB/PS/NM	NM/ZE/ZE	NM/PS/NB
PS	NM/ZE/NS	NM/ZE/NM	NM/NS/ZE	NM/ZE/NM
ZE	NS/NS/NS	NM/NS/NS	NM/NS/ZE	NM/ZE/NM
NS	ZE/ZE/NS	ZE/ZE/NM	NS/NS/NM	NS/NS/NM
NM	PS/PS/NS	PS/PS/NS	ZE/PS/NM	ZE/PS/NM
NB	PM/PB/ZE	PS/PB/ZE	ZE/PB/PS	ZE/PM/PS

The Fuzzy Control Rules can be transferred to PID form. From formula (7) the control signal can be represented into the combination of proportion, differential and the rate of differential. Table 1 is a 2-D fuzzy control rules. The 3-D fuzzy rules of E, EC, ECC is similar to table 1.

3. Fuzzy Controller Algorithm

In order to get the control signal, the key point is to get the fuzzy relationship matrix R:

$$R_i = e_i \times ec_j \times u_{ij} \quad (8)$$

$$R = \sum_{i=1}^{n} R_i \quad (9)$$

$$U = [e(k) \times ec(k)] \circ R \quad (10)$$

where e_i , ec_j and u_{ij} are the error, error change, corresponding control in i^{th} sample time. All these signals are represented in the form of fuzzy signal. From (10) we can get the fuzzy control signal.

4. Fuzzy Decision

To attain the real control signal, the Fuzzy control signal should be transferred into practical control signal. A Fuzzy Decision is introduced here.

$$u_c = \sum_i u(Z_i) \bullet Z_i \Big/ \sum_i u(Z_i) \quad (11)$$

where $u(Z_i) = U_i$ is the i^{th} value of the fuzzy control and u_c is the control signal that can be directly used. Fuzzy Logic often employs this method because some useful information will not lose here.

IV. Simulation and Discussion

In this section, a DC motor is set as an example. Here we define the transfer function of DC motor as follows:

$$\dot{\mathrm{x}} = \begin{bmatrix} 1 & 0 \\ -1 & 0 \end{bmatrix} \mathrm{x} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \mathrm{u} \quad (12)$$

$$\mathrm{y} = \begin{bmatrix} 0 & 1000 \end{bmatrix} \mathrm{x} \quad (13)$$

The design requires that overshot is less than 2%, the steady-state error is less than 2%, and the rising time is less than 0.2s.

Through the abovementioned method, the total process is as follows. When the error is big, then the control should be big in order that the system responses quickly. At this time, the error weighs greater than the change error in determining the control. When the error is small comparing with reference signal, the control should be small to eliminate high overshoot. At this time, the change of error has higher priority than the error when fixing on the control. Further, the change of error represents how fast the output approaches the reference.

From Fig.3 above, we can see that the performance of Modified PID control is better than Classic PID controller. The overshoot is less than 1%. As the control signal includes three parts, the high-order information can be offered in the Modified PID Controller. At the same time, long delay contains more high-order information; therefore the Modified PID is proved better. Here, we can see that the delay degrades the system performance significantly with Classic PID controller, while the Modified PID controller adapts the delay well.

From Fig.4 we can see the relationship between the error and the control: When the error is big (negative big at the beginning), the control is positive big comparing with late control information. But when the output increases sharply, that is, the change of error increments, the control decreases sharply, too. That is because the control is determined not only by error but also by the change of error.

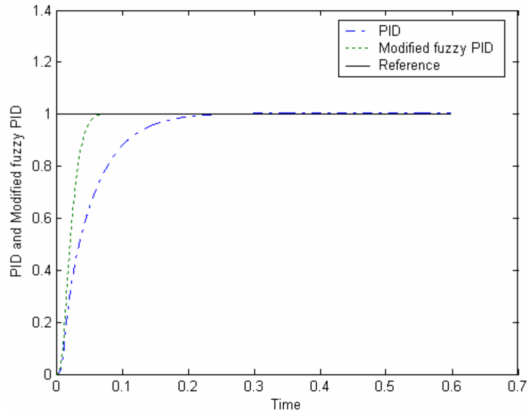

Fig. 3 Comparison between PID and Modified fuzzy PID

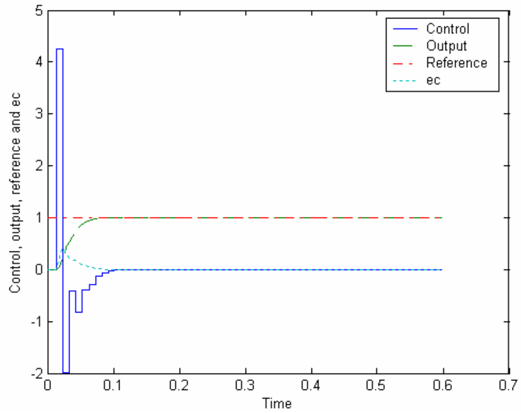

Fig. 4 Control, Output, Reference and ec

From Fig.4 we can see the change of error affects the control signal. If we just consider the effect of the error, we can know that the control should be positive all the time as the error is negative. However, the dynamic performance deserves consideration of the system inertia, that is to say, to consider the change of error. The continuity of the change of error calls for reducing the control signal to give better performance. In addition, the change of error shows how fast the output approaches the reference.

From Fig.5 we can see that the rate of error change approximately shows the trend of change of control, that is, when the rate of error change is positive, the control will increase; when the rate of error change is negative, the control will decrease. If the change of the rate of error change is large, the change of control is large. The rate of error change determines the rate of the change of error. In another word, when the output approaches the reference, the change of error should be small and mainly keep the same. Thus the rate of error change embodies an important factor in the system performance.

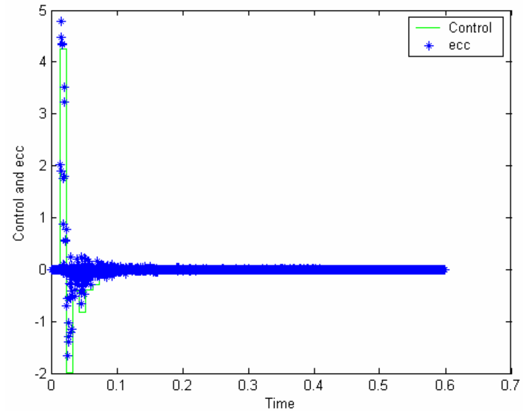

Fig. 5 The rate of error change and control

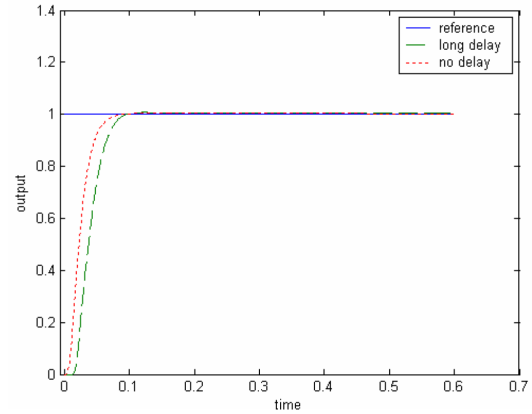

Fig. 6 Comparison with different delays

To see the advantage and good performance in closed-loop control of NCS when the network delays are unstable, we use the step response of a network-based DC motor to track the step signal. From the above picture we can see that the Modified PID Controller gives better performance than Classic PID Controller in bother the process and the final output. When the delay is long, the high-order information is added here to provide accurate approximation of the nonlinear caused by delay. Since the performance is partly determined by the network, high network QoS can give better performance than low network QoS (see Fig.6). Table 2 shows different dynamic performance of NCS with high QoS and low QoS.

TABLE II
DYNAMIC PERFORMANCE OF NCS WITH DIFFERENT QOS

Symbol	Low QoS	High QoS
Overshoot	0.7%	0.4%
Transition time	0.0815s	0.0667s
Rise time	0.0445s	0.0370s
Delay time	0.0389s	0.0204s
Peak time	0.1222s	0.1518s

V. CONCLUSION

Fuzzy PID controller has shown its benefit in dealing with random delays in NCS due to its flexibility and adaptation to uncertain elements. In this paper Modified PID controller supplies high-order information that can accurately track the nonlinear of delays. It is noticeable that this method presents good performance. Nevertheless, none of the Fuzzy PID controllers can be perfect because of the nonlinear of the delay.

As Fuzzy Logic is a study process, what kind of membership functions is better and how many fuzzy parameters are proper are still problems. In addition, with the growing requirement of the system performance, the fuzzy membership functions and the inference rules becomes more and more complicated. Therefore, to choose a simple, accurate fuzzy controller is still a problem.

This paper shows the Modified PID controller applied in DC motor give good performance. We know from this paper that the high-order information can give additional information that can improve the system performance.

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